



# Effect of facing type on the behaviour of soil-nailed slopes: centrifuge and numerical study

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## General Note



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## ABSTRACT

This paper evaluates the significance of slope facing on the stability and deformation behaviour of soil-nailed slopes subjected to seepage. A short series of centrifuge tests was performed to study the behaviour of 5V:1H soil-nailed slopes with and without slope facing by maintaining the model slope height (240 mm) with horizontal back slope, nail inclination of 10° with horizontal and model nail spacing of 60 mm x 60 mm constant at 30 gravities. Effect of flexible as well as stiff facing on the performance of soil-nailed slopes was also studied. All models were instrumented with displacement and pore water pressure transducers and markers were digitized to arrive at displacement vectors with rising ground water table during centrifuge tests. It was observed that the slope facing prevents the local failure of the soil between the nails. Soil-nailed slope without facing was found to experience face failure due to bearing failure at slope surface and nail head surface as well as due to built up of excess pore water pressure at the toe region after 8.5 days of the seepage. Soil-nailed slope with woven geotextile (flexible) facing experienced 0.18 m of crest settlement and bulging of facing was observed in between nail heads. However, a soil-nailed slope with an aluminium facing was found to sustain large settlements and showed improved deformation behaviour at the onset of seepage. Further, finite element analyses of the slope models with and without slope facing were found to be in good agreement with those of physically observed centrifuge test results.

**Keywords:** Centrifuge modeling, Model tests; Slope stabilization; Soil-nailing; Seepage.

## 1. INTRODUCTION

Soil nailing is an earth reinforcement technique that can be used to support or stabilize existing slopes for ensuring the stability and satisfactory performance of the permanent structure being supported. Facing of a soil-nailed slope is one of the important components that influence the deformation behaviour of a soil-nailed slope and should be studied properly. The effect of facing stiffness on the performance of soil-nailed slopes was studied earlier by several investigators through numerical, full-scale and small-scale (at normal and high gravity) studies. Ehrlich et al. (1996) performed parametric numerical studies to find out the effect of facing stiffness on the behaviour of soil-nailed slopes and reported that the facing stiffness could help to control the yielding of the soil close to the facing. Shiu and Chang (2005) carried out numerical simulations using FLAC and observed that maximum tensile forces in nail increased with an increase in percentage of slope surface area covered by nail head. Muramatsu et al. (1992) conducted a series of full-scale field tests to investigate the effect of slope facing on soil-nailed slopes and concluded that the flexible shotcrete facing was less effective in improving the overall stability of the slope. Gutierrez & Taksuoka (1988) conducted loading tests on three model sand slopes which were: (i) unreinforced slope, (ii) slope reinforced with metal strips and without a facing, and (iii) slope reinforced with metal strips and facing. It was reported that the reinforced slope with facing sustained the highest load and facing enhanced the stability of reinforced slope. For the reinforced slope without facing, failure occurred near the slope face. This was because of that only reinforcement was less effective in retaining the active zone. (Ming 2008) carried out a series of small scale model tests and reported that stability of the reinforced slopes was influenced by the proportion of the slope face supported by the nail head or facing.

The effect of facing types on the performance of soil-nailed slopes was also studied through centrifuge model tests by several investigators. Frydman et al. (1994) carried out centrifuge model tests on a vertical cut stabilized with soil nails along with a geotextile facing. It was observed that slope facing significantly affected the stability of the nailed excavations. Tei et al. (1998) performed series of centrifuge model tests and reported that flexible facing showed more horizontal deflection than stiff facing. Morgan (2002) observed bulging of flexible slope facing (using woven geotextile) between nail heads at the bottom of the slope and suggested that a stiffer facing with greater bending strength could restrict displacement and bulging of slope facing. Rotte and Viswanadham (2012, 2013) observed that facing helped to retain the soil mass effectively behind it and it prevented the local failure of the soil between the nails at the toe of slope. The deformation behaviour of soil-nailed slopes subjected to seepage was also observed to influence by stiffness and facing material type. Soil-nailed slope without slope facing failed to avoid local failure at the toe of the slope at the onset of seepage (Tei et al. 1998, Viswanadham and Deepa 2010). The objectives of this paper is to present further findings on the necessity of slope facing and influence of facing stiffness on the stability and deformation behaviour of a soil-nailed slope subjected to seepage.

## 2. CENTRIFUGE MODEL TESTS ON SOIL-NAILED SLOPES WITH AND WITHOUT SLOPE FACING

### 2.1. Centrifuge Modelling Technique

Centrifuge modeling technique can be widely used for number of problems in geotechnical engineering. It allows small-scale models to be tested under increased gravitational acceleration to achieve full-scale stress levels. In this study, centrifuge experiments were performed at 30 times the Earth's gravity ( $g$ ) using the large beam centrifuge facility available at Indian Institute of Technology Bombay, India (Viswanadham and Deepa, 2010). An onboard central processing unit placed on the swing basket allows to record data from various transducers continuously. The scaling considerations of parameters related to soil, slope and soil-nails need to be satisfied and are discussed by Rotte and Viswanadham (2013).

### 2.2. Experimental Materials

#### 2.2.1 Model Soil

In the present study silty sand was used as a model soil. It was a mixture of locally available poorly graded Goa sand and a blend of commercially available kaolin in the proportion of 80:20 by dry weight. Purposefully, this type soil was adopted to allow seepage of water during centrifuge tests in a short duration. It had a specific gravity of 2.63, a maximum dry unit weight ( $\gamma_{dmax}$ ) of 18.75 kN/m<sup>3</sup> and optimum moisture content (OMC) of 9% (standard Proctor compaction). Consolidated undrained triaxial tests were carried out on samples moist-compacted at  $\gamma_{dmax}$  and OMC. The shear strength parameters of model soil were 12.5 kN/m<sup>2</sup> in cohesion and 28.3° in an internal friction angle. The coefficient of permeability  $k$  of the soil moist-compacted at  $\gamma_{dmax}$  and OMC was found to be  $1.54 \times 10^{-6}$  m/s.

### 2.2.2 Model Nails

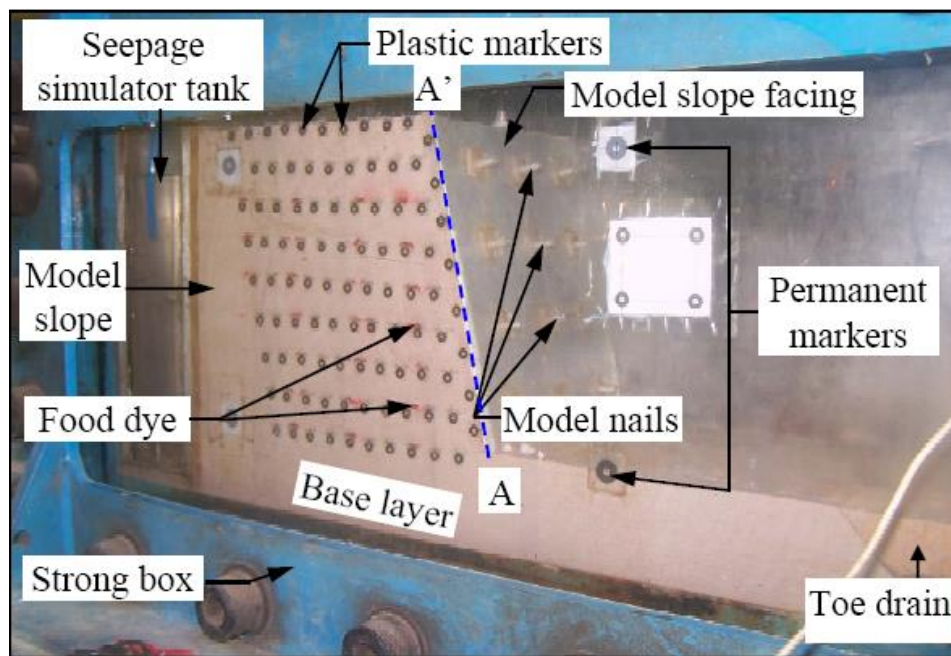
Soil nails were modeled using aluminum tubes of 6 mm diameter and thickness of 0.5 mm. A 1.25 mm thick layer of epoxy covered with standard sand (Grade I) was applied on the surface of aluminum tube to simulate the interface behavior between grout and surrounding soil. Modified saturated direct shear tests were performed to determine the interface friction angle between standard sand (Grade I) smeared aluminium plate and model soil. It was found to be 0.83. Length of the nail within the slope was maintained 200 mm in model dimensions. The nail head was modeled using a 6 mm thick acrylic sheet of 20 mm x 20 mm size. Key pins were used to keep the acrylic sheet in place.

### 2.2.3 Model Slope Facing

Nail head capacity is one of the important parameters used in the design of soil-nailed structures. Based on previous studies and scaling considerations for slope facing, two types of facing materials woven geotextile and 2 mm thick Aluminium sheet were selected. Woven geotextile was modeled as flexible facing and aluminium sheet as stiff facing. The properties of woven geotextile were considered as discussed by Raisinghani (2011). Holes of 9 mm diameter were drilled to the slope facing according to the nail layout designed for a soil-nailed model slope to be tested.

## 2.3 Test Package, Programme and Procedure

Figure 1 depicts a view of model soil-nailed slope with stiff facing (VBS 6). A strong box of 0.76 m long, 0.20 m wide and 0.41 m high internally was used for the experimental program. The other details of the strong box and the procedure followed to reduce the friction effects and to approximate plane-strain conditions were discussed by Deepa and Viswanadham (2009). A seepage simulator unit was used to allow seepage of water through soil-nailed slopes during the tests. The details and working operations of seepage simulator unit was discussed in detail by Rotte and Viswanadham (2013).

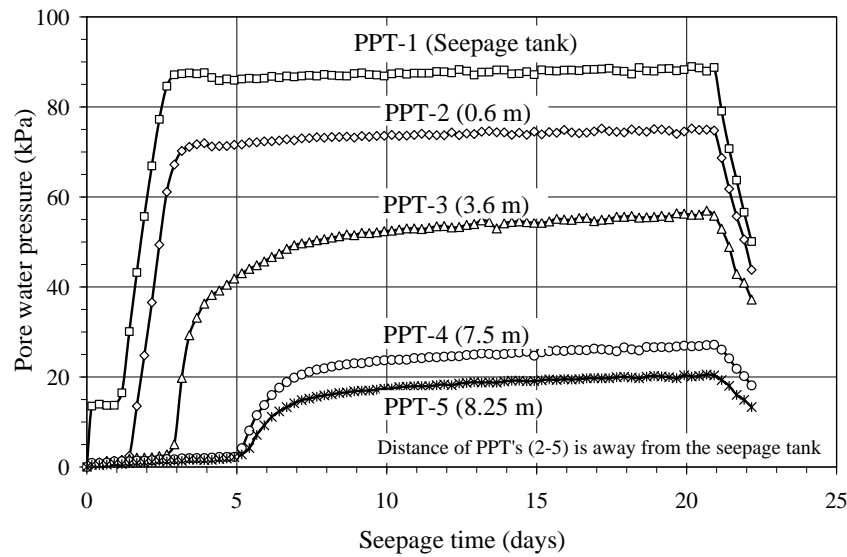


**Figure 1** View of model soil-nailed slope with stiff facing (VBS-6)

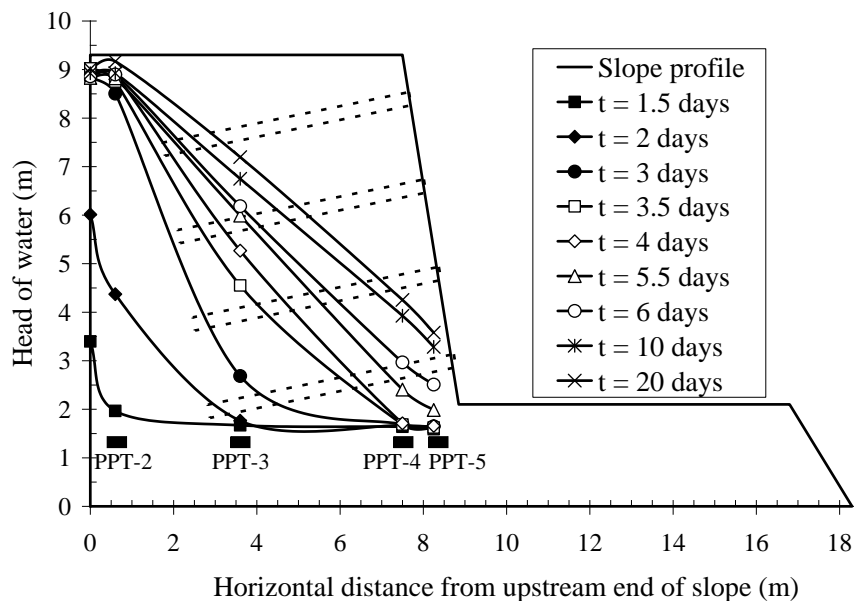
A rectangular grid (350 mm x 210 mm) of permanent markers was pasted firmly on the inner side of the Perspex sheet. The model slope of 240 mm high was constructed in layers of 30 mm thickness using moist compacted soil at its  $d_{max}$  and OMC. The slope model was built on a 70 mm thick base layer using the same soil. After completion of each layer, specially designed L-shaped plastic markers made of thin transparency sheets were placed at a distance of 20 mm from the slope face to study the movement of soil during the test. The detailed procedure of construction of slope model, insertion of nail with facing was discussed in detail by Rotte and Viswanadham (2013). All the slope models were instrumented with the help of pore pressure transducers (PPTs) to

measure the development of pore water pressure within the slope and linearly variable displacement transformers (LVDTs) to record the surface settlements of the slope during the test.

All the centrifuge tests were performed on 5V:1H soil-nailed slopes with and without slope facing by maintaining the model slope height (240 mm), nail inclination of  $10^\circ$  with horizontal and model nail spacing of 60 mm x 60 mm constant at 30 gravities. Soil-nailed slope model VBS-4 is without slope facing. Model VBS-14 is with flexible (using woven geotextile) facing and Model VBS-6 is with stiff (2 mm thick aluminium plate) facing. Model VBS-4 was compared with models VBS-14 and VBS-6 to bring-out the efficacy of slope facing for soil-nailed slopes subjected to seepage. Models VBS-14 and VBS-6 were used to study the effect of slope facing stiffness on the behaviour of soil-nailed slopes. After reaching 30 g, water was allowed to seep through the model slope and its behavior was observed until global failure or localized failures occurred. Each soil-nailed model test proceeded for 40 min (which implies 25 days in prototype dimensions at 30g) until global failure or constant variation of surface settlements, whichever occurred earlier. Physical status of the soil-nail reinforced slope models was recorded by capturing images at every 30 second intervals with the help of a digital camera. The data from the LVDTs and PPTs were obtained using an on-board data acquisition system.



**Figure 2** Variation of pore water pressure with seepage time (VBS 6)



**Figure 3** Developed phreatic surfaces at various seepage time (VBS 6)

### 3. ANALYSIS AND INTERPRETATION OF CENTRIFUGE MODEL TESTS

All the centrifuge model tests were aimed to study the necessity and influence of slope facing stiffness on the performance of soil-nailed slopes subjected to seepage. Figure 2 presents the variation of measured pore water pressure within the soil at the onset of seepage for model slope VBS 6. PPT1 was located within the seepage tank, shows the steady state seepage conditions were achieved during the centrifuge tests. The locations of remaining PPTs (PPT2 - PPT5) are shown in Fig.3. From the PPT readings the phreatic surfaces were obtained during various stages of seepage. Figure 3 depicts the developed phreatic surfaces at various time of seepage within the soil-nailed slope with stiff facing (VBS-6) in prototype dimensions.

The variations of surface settlements with horizontal distance at various values of normalized pore water pressure ( $u/\gamma H$ ) for PPT3 are shown in Figs. 4a-c. Normalized pore water pressure ( $u/\gamma H$ ) was defined as the ratio of the pore water pressure measured by PPT3 placed at mid-distance from crest of the slope to the product of bulk unit weight of the model soil and slope height  $H$ . As seepage increases, the surface settlements were observed to increase and were found to be maximum for LVDT L1 placed at the crest. The maximum crest settlement observed for soil-nailed slope without facing was 1.63 m. The soil-nailed slope with flexible facing settled at the crest by 0.145 m whereas for the soil-nailed slope with stiff facing, the maximum crest settlement was 0.05 m. The values of the slope face movements measured with the help of markers pasted to a facing element were used to quantify face deformations of soil-nailed slope models. Figures 5a-c present face movements with  $Z/H$  for models VBS-4, VBS-14 and VBS-6 respectively. These plots were derived based on the movements of markers from the beginning to the penultimate stages of the test in both vertical and horizontal directions. For convenience, the slope face movements were plotted along axis A-A', as shown in Fig. 1. Soil-nailed slope (VBS-4) without slope facing, experienced face movement equal to 2.3 m at the toe portion. However, model VBS-14 reinforced with nails and woven geotextile slope facing registered face movements equal to 1.3 m and bulging of flexible facing was observed to be prominent in between nail heads. The soil-nail reinforced slope with stiff facing was observed to experience a marginal lateral movement of 0.09 m in the top-half portion of the slope.

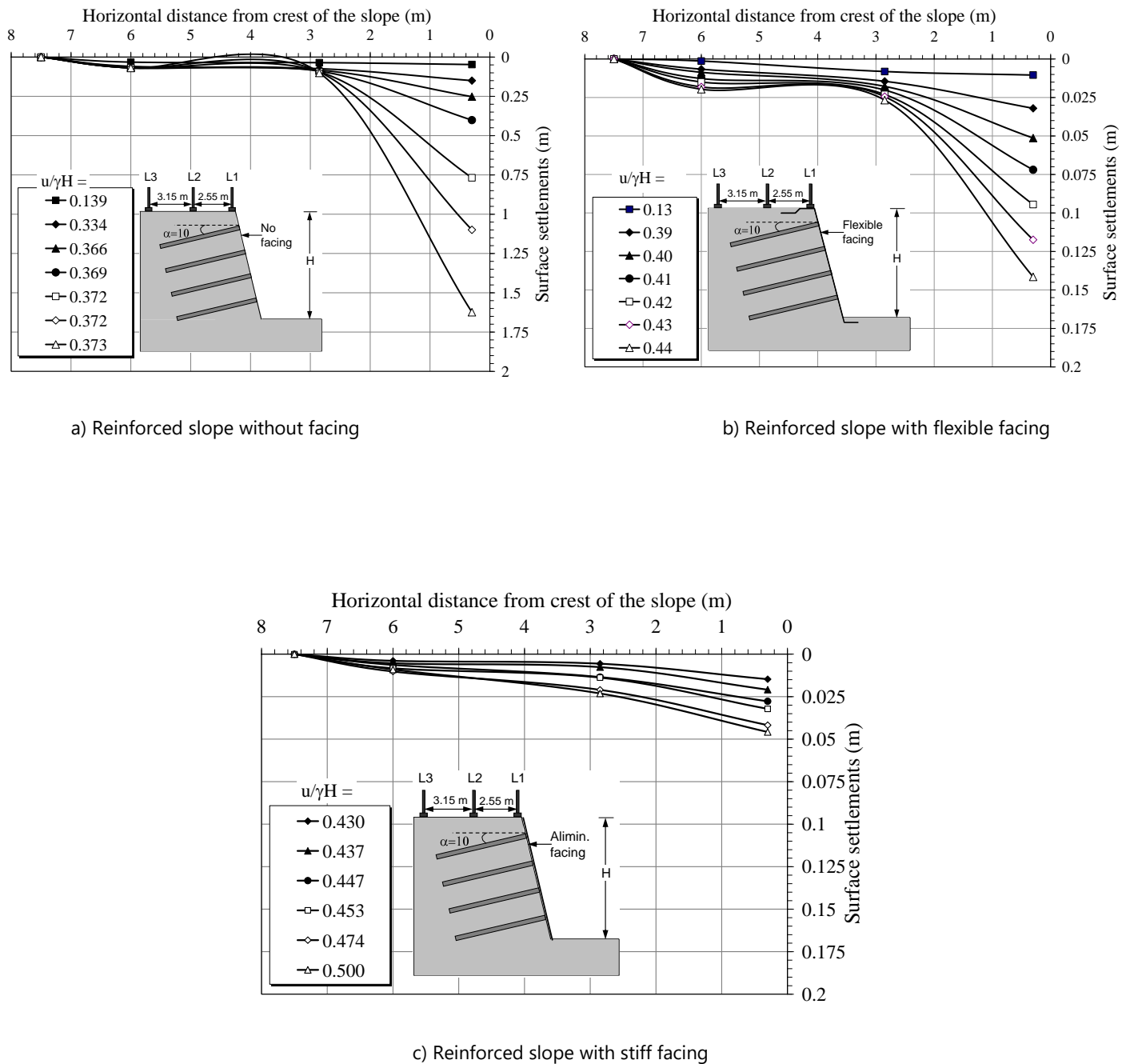
### 4. FINITE ELEMENT ANALYSIS OF SOIL-NAILED SLOPES

A finite element analysis (FEA) of soil-nail reinforced slopes with and without slope facing was performed in this study using PLAXIS 2D (version 2010), a geotechnical finite element code. The present study is simplified as a plane strain problem. Boundary conditions were selected similar to those in centrifuge model tests in prototype dimensions. The analysis was conducted in three phases: (a) Gravity loading, (b) Plastic drained analysis and (c) Safety analysis. For each model the initial stress generation is necessary and it is recommended to use gravity stress generation process for retaining structures (PLAXIS 2D, 2010). The phreatic surface was positioned at the base of the model to avoid its effect on the gravity analysis results. After successful completion of stress generation process plastic analysis step was introduced subsequently. In the plastic drained analysis phase, elastic-plastic deformation analysis is carried out. Phreatic surface was introduced within the slope as obtained in centrifuge tests and was followed by the generation of steady state seepage condition. The model was allowed to deform under the seepage pressure condition. The third phase consists of safety ( $\phi$ -c reduction) analysis which includes the successive reduction of  $\phi$  and  $c$  of the soil until the failure occurs in the soil-nailed slope. Soil elements used in finite element analysis (FEA) were six-noded triangular iso-parametric elements. The Mohr–Coulomb constitutive model was used to model the stress–strain behaviour of soils. The program automatically determines clusters based on the input geometry.

Within the cluster the soil properties are homogeneous. Rectangular shaped structural element 'Plate' was used to simulate soil-nails and slope facing in FEA. The 'Plate' structural elements are rectangular in shape with width equal to 1 m in out-of-plane direction. Nails were modelled using elastic-perfectly-plastic behaviour, with a limiting tensile force ( $T_p$ ) and maximum bending moment ( $M_p$ ). The axial stiffness (EA) and flexural rigidity (EI) of soil-nails and slope facing used in the centrifuge study (in prototype dimensions) were adopted as input parameters in FEA. Numerical modelling of the soil-nailed slope studied herein was validated with results on soil-nailed slopes published by Fan and Luo (2008). The significance of facing stiffness on the performance of soil-nailed slopes was studied in terms of factor of safety, deformation behaviour of soil-nailed slopes and distribution of nail forces. The deformation profiles and variation of nail forces for soil-nailed slopes with and without facing are shown in Figs. 6-7.

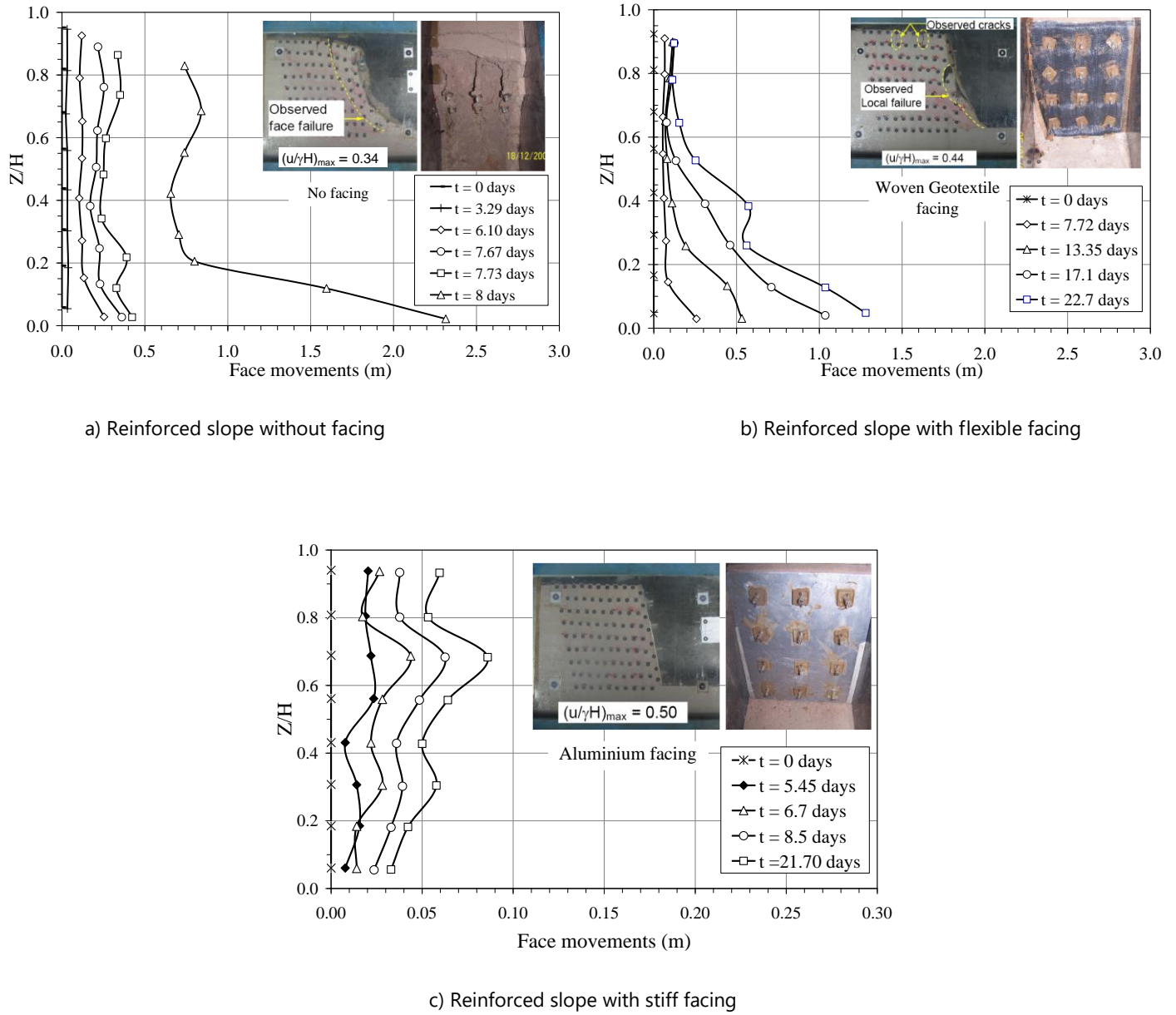
However, for soil-nail reinforced slope with stiff facing, maximum deformation was 0.06 m and FOS was equal to 1.18. Soil-nailed slope without facing deformed more than slope with flexible and stiff facing. This shows that performance of soil-nailed slopes with stiff facing is superior to the soil-nailed slopes without facing and with flexible facing. Figure 8a depicts the variation in  $(F_{N, \max}/\gamma H^2)$  along the normalized depth ( $Z/H$ ) of the slope with various  $u/\gamma H$  values for soil-nailed slopes with and without slope facing. In this paper,  $F_{N, \max}/\gamma H^2$  is defined as the ratio of developed maximum axial force in nail to the product of bulk unit weight of model soil and square of the slope height. Developed nail forces were observed to increase with an increase in  $u/\gamma H$  values and along the depth of the slope for all the soil-nailed slopes. Soil-nailed slope with stiff facing experienced less nail forces as compared to slopes

without and with flexible facing. In the absence of a slope facing and with flexible facing, stability of the slope was maintained by the developed forces in nails only. Deformation profiles for soil-nailed slopes with and without facing are shown in Fig. 8b. Crest settlement for soil-nailed slope without facing was observed to maximum as compared to slope with flexible and stiff facing. For soil-nailed slope with stiff facing crest settlement was minor. These observations confirm the necessity and effect of facing stiffness on the behaviour of soil-nailed slopes subjected to seepage. As can be noted from Figs. 5-7, FEA results were found to corroborate well with physically observed centrifuge test results.

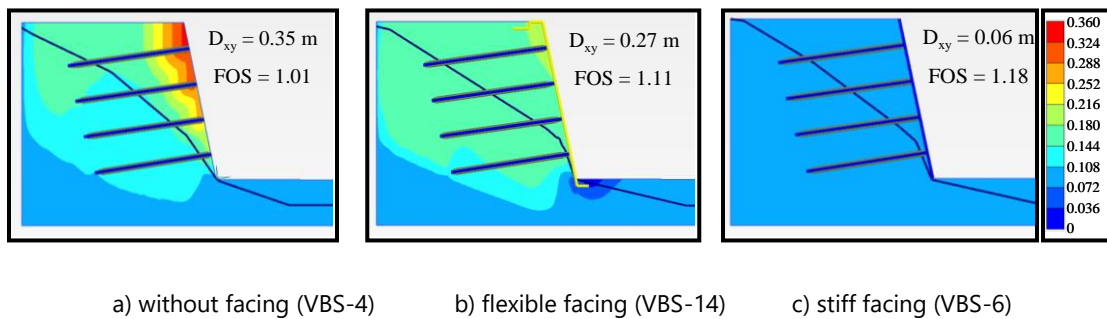


**Figure 4** Variation of surface settlements with horizontal distance from crest of the slope (in prototype dimensions)

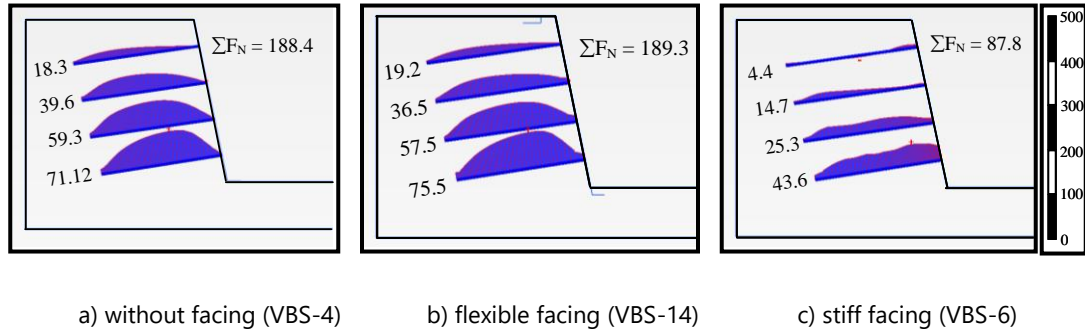




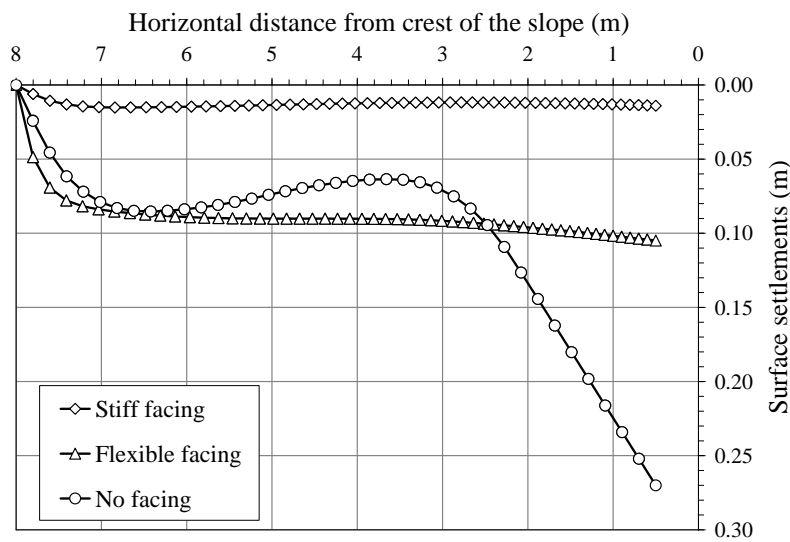
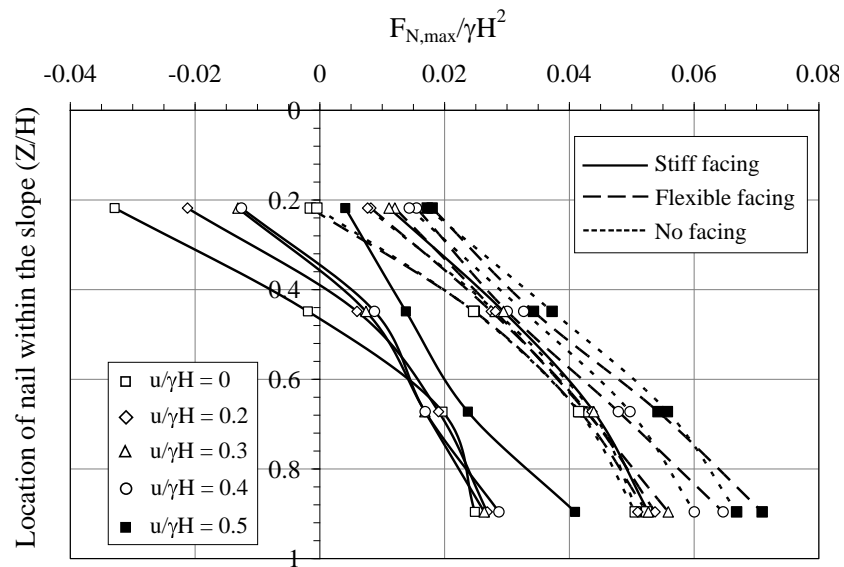
**Figure 5** Lateral displacements at the onset of seepage through soil-nailed slopes (in prototype dimensions)



**Figure 6** Deformation profiles for soil-nailed slope with and without slope facing



**Figure 7** Variation in nail forces for soil-nailed slopes with and without slope facing (nail forces are in kN/m)



**Figure 8** FEA results of soil-nailed slopes with and without slope facing



## 5. CONCLUSIONS

This paper presents centrifuge model studies on the necessity of slope facing and the effect of slope facing stiffness on the performance of soil-nailed slopes subjected to seepage. Based on the data obtained from the centrifuge model tests and FEA carried out on soil-nailed slopes with and without slope facing, the following conclusions are drawn:

1. Soil-nailed slope without facing experienced a crest settlement of 1.63 m with  $S_c/H = 0.226$ . However, both the soil-nailed slopes with flexible and stiff facing registered a maximum crest settlement of only 0.145 m with  $S_c/H = 0.02$ . This implies that the slope facing is one of the most important components of a soil-nailed slope and effective in improving the stability and deformation behaviour when subjected to seepage.
2. Reinforced slope with flexible facing showed local failure at the edges and bulging of the facing was observed between the nail heads. However, soil-nailed slope with rigid facing was found to be stable for seepage time more than 21 days in prototype dimensions. Maximum crest settlement for reinforced slope with flexible facing was 0.145 m (2 % of the height of slope) and for reinforced slope with stiff facing, was 0.05 m (0.7% of the height of slope). Thus, stiffness of slope facing is one of the influencing parameters that can affect the deformation behaviour of soil-nailed slopes.
3. Results of FEA indicate the significance of both stiff facing and soil-nails in improving the stability and deformation behaviour of soil-nailed slopes. Moreover, with stiff facing, the pattern of force mobilization is found to be different than a soil-nailed slope with flexible facing. This could be attributed to mobilization of adequate bearing strength at nail-heads interacting with stiff facing. Finally, both centrifuge test results and FEA show the significance of facing stiffness on the performance of soil-nailed slopes.

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## REFERENCE

1. Deepa, V., and Viswanadham, B. V. S. (2009). "Centrifuge model tests on soil-nailed slopes subjected to seepage." *Ground Improvement. J.*, 162(3): 133-144.
2. Ehrlich, M., Almeida, M.S.S., and Lima, A.M. (1996). "Parametric numerical analyses of soil nailing systems." *Proc. Int. Symposium on Earth Reinforcement*, Balkema, Rotterdam, Fukuoka, Japan, 747-752.
3. Fan, C.C. and Luo, J.H. (2008). "Numerical study on the optimum layout of soil-nailed slopes." *Computer and Geotechnics* 35(4): 585-599.
4. Frydman, S., Levy, A., and Baker, R. (1994). "Modelling the soil nailing-excavation process." *Proc., Centrifuge 94*, Balkema, Rotterdam. Singapore 669-674.
5. Gutierrez, V., and Tatsuoka, F. (1988). "Role of Facing in Reinforcing Cohesionless Soil Slopes by Means of Metal Strips." *Proc. Int. Geotechnical Symposium on Theory and Practice of Earth Reinforcement*, Balkema, Rotterdam, Fukuoka, Japan, 289-294.
6. Ming, C. Y. (2008). "Centrifuge and three dimensional numerical modelling of CDG filled slopes reinforced with different nail inclinations." *M.Phil. dissertation*, Hong Kong University of Science and Technology, Hong Kong.
7. Morgan, N. (2002). The influence of variation in effective stress on the serviceability of soil-nailed slopes. *Ph.D. Thesis*, University of Dundee, UK.
8. Muramatsu, M., Nagura, K., Sueoka, T., Suami, K., and Kiramura, T. (1992). "Stability analysis for reinforced cut slopes with facing." *Proc. Int. Symposium on Earth Reinforcement Practice*, Balkema, Rotterdam, Japan, 503-508.
9. PLAXIS (2010). "Plaxis 2D Reference Manual, Version 10." Delft, Netherlands.
10. Raisinghani, D. (2011). Studies on the performance of hybrid geosynthetic reinforced slopes. *Ph.D. Thesis*, Dept. of Civil Engineering. IIT Bombay, India.
11. Rotte, V.M., and Viswanadham, B.V.S. (2012). "Performance of 2V:1H slopes with and without soil-nails subjected to seepage: Centrifuge study." *Proc., Geo-Congress 2012, Geotechnical Special Publication 225* (CD-ROM), ASCE, Oakland, CA, USA.
12. Rotte, V. M., and Viswanadham, B.V.S. (2013). "Influence of nail inclination and facing material type on soil-nailed slopes." *Ground Improvement J.*, 166 (2): 86-107.
13. Shiu, Y.K., and Chang, G.W.K. (2005). "Effects of inclination,

length pattern and bending stiffness of soil nails on behaviour of nailed structures." *Geo Report No.197 Civil Eng. and Develop. Dept., Govt. of Hong Kong.*, 1-116.

14. Tei, K., Taylor, R. N., and Milligan, G. W. E. (1998). "Centrifuge model tests of nailed soil slopes." *Soils and Foundation*, 38 (2): 165-177.
15. Viswanadham, B. V. S., and Deepa, V. (2010). "Evaluation of performance of soil-nailed slopes subjected to seepage in a centrifuge." *Proc., 7<sup>th</sup> Int. Conference on Physical Modeling in Geotechnics 2010*, Taylor and Francis, London, 1151-1156.